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DISCUSSION OF THE GEOCHEMISTRY OF EARTHWORK

(Published in March, 1950)

By Warren D. Smith, D. P. Krynine, S. S. Gorman, Charles H. Lee, George S. Harman, and Hyde Forbes

SOIL MECHANICS DIVISION

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DISCUSSION

WARREN D. SMITH.[8]—A subject of paramount importance to engineers, and one very inadequately treated in textbooks on engineering geology, has been opened for discussion by Mr. Forbes.

Many engineers have studied little or no geology in their academic curriculum. This lack, however, does not belittle their competence as engineers, for only within recent years has the importance of geology been adequately recognized. The writer knows of one recently published engineering school curriculum in which no course in either geology or mineralogy is provided. A civil engineer should have some knowledge of the earth on which he is going to erect his structures. It is not enough to hire a geologist and leave the problem entirely to him. The engineer should know enough geology to enable him to cooperate with the geologist and appreciate the significance of geological findings.

Many of the reactions and principles brought out in Mr. Forbes' valuable paper have long been known to geologists,[9] but they have not been applied very widely to concrete practical engineering problems. According to Charles R. Van Hise[9] the crust of the earth is not static—there are changes continually taking place, either those that are anamorphic, like cementation, or those that are katamorphic, in which breakdown and disintegration are the rule. Through his activities, man often promotes these reactions and, if he does not realize this, he can get into serious difficulties.

Some of Mr. Forbes' examples from actual observations in practical work illustrate extremely well these metamorphic processes, as, for instance, the effect of water in earth fill construction on the Swanzy Dam in Vallejo, Calif. Again he cites the failure to understand the nature of the materials in the abutments of the St. Francis Dam[10] in California which led to that regrettable disaster.

The writer has observed numerous examples of profound geochemical changes which, if overlooked, lead to serious engineering troubles with landslides and rockfall. In western Oregon and Washington, for example, where there are certain types of rocks, tertiary volcanics, and sediments derived from them, in a region of copious rainfall, one can expect an unusual degree of weathering and, consequently, frequent landslides and rockfalls. This means that the slopes bordering all highways and railroads should be much lower than in other regions where these conditions do not prevail. Failure to realize these conditions has cost the State of Oregon, and railroad companies, great sums of money.

NOTE.—This paper by Hyde Forbes was published in March, 1950. The numbering of footnotes and of the table in this Separate is a continuation of the consecutive numbering used in the original paper.

[8] Prof. Emeritus, Dept. of Geology, Univ. of Oregon, Eugene, Ore.

[9] "A Treatise on Metamorphism," by Charles R. Van Hise, U. S. Govt. Printing Office, Washington, D. C., 1904.

[10] "Essential Facts Concerning the Failure of the St. Francis Dam: Report of Committee of Board of Direction," *Proceedings*, ASCE, October, 1929, p. 2147.

Nature makes no allowance for ignorance. Engineers must know more about geochemical processes—"or else!" This need resolves itself into four recommendations as follows:

1. Civil engineers should include more geology in their academic curriculum.
2. On all important civil engineering projects geologists with some knowledge of geochemistry should be consulted.
3. Researches in this field should be liberally supported. (Excellent work is now being done by several organizations, including that of the Bureau of Reclamation on the alkali problem in connection with concrete construction.)
4. Finally, there should be more frequent symposium discussions of the many aspects of this general subject of geochemistry, in which engineers, physical chemists, geologists, and contractors could take part.

Mr. Forbes has made a constructive contribution to a subject of first importance to all who are concerned with practical problems connected with the crust of the earth.

D. P. KRYNINE,[11] M. ASCE.—The constituents of the earth crust are never in a state of static equilibrium. Obeying the well-known rule of boundary conditions they tend to attain equilibrium with the environment. In turn, the latter is also variable because of the changes in temperature, humidity, pressure, and other factors. When extracted from the earth crust and placed in an engineering structure, materials such as rock and soils tend to attain the state of equilibrium with the new conditions of work. Hence, their behavior may substantially differ from that under natural conditions. It is decidedly advantageous for engineers to understand the geochemical processes that may develop in this connection, in order to avoid possible surprises.

Without presenting a comprehensive discussion of this interesting paper, the writer wishes to emphasize only two important topics—field decomposition of calcium carbonate and changes in specific gravity.

Field Decomposition of Calcium Carbonate.—The author depicts the decomposition of calcite in the sandstone foundation rock of the Gibraltar Dam on the Santa Ynez River, in California, as breaking of the calcium carbonate into lime and carbon dioxide. As the author states (under the heading, "Weathering, a Geochemical Change Through Geologic Processes"):

> "The site was stripped to fresh, sound rock and hosed off before pouring concrete; but overnight it slaked and the surface became covered with rock flakes, sand, and white, chalk-like dust. This loose matter was cleared with wire brushes, and again the detritus formed before concrete was poured."

The constituents of a sedimentary rock such as sandstone are: (*a*) Grains, (*b*) matrix or a groundmass of smaller grains in which the larger size grains are embedded, and (*c*) cement that infiltrates around grains and matrix. In the present case the cementing material was (at least partly) the product of decomposition of fossil shells consisting of the grains of calcite bound together with amorphous calcium carbonate (or more accurately microcrystals) as is

[11] Cons. Engr., San Francisco, Calif.

the case of limestone. Chemically, the so-called high calcium limestone and calcite consist almost entirely of calcium carbonate. What was reduced to dust in the case described by the author was probably the apparently amorphous mass (microcrystals) bounding the crystals of calcite.

The deterioration of limestone and the decomposition of the calcite are very common troubles in the building stone industry; and besides breaking into lime and carbon dioxide (as, according to the author, was the case of the Gibraltar Dam); the given material may undergo other deteriorations with the same general picture of failure as that given by the author. More specifically, the writer wishes to refer to the views of some French geologists and scientists[12] on the process of the field decomposition of calcium carbonate, which is defined in that case as a transformation of a part of the calcium carbonate mass into calcium sulfate (gypsum). Contrary to popular belief, such transformations are not limited to localities affected by smoke but may occur anywhere—as, for instance, examples were found in some old French country churches. The transformation itself is due to a base exchange process; and this reaction, being ionic, requires water for its completion. Hence, humidity is an essential factor for such transformations. On the other hand, sulfur salts are required for that reaction. In country districts, sulfur salts are practically absent in the meteoric water, such as rain water; but this water may acquire the necessary salts during its passage through soil, from which water is afterward pulled up by capillarity. In industrial cities, of course, rain water contains enough sulfates. Without entering into details, it also may be stated that the process of deterioration is accompanied and activated by bacteria.

In the final analysis the rotten rock possesses a thin, impervious, hard crust followed by a zone of deterioration that, being exposed, resolves into yellowish friable powder. A stripping of the outer surface of such a rock would cause pulverization of the exposed surface.

The writer ventures to believe that, in the case of the Gibraltar Dam, the rock was already in an advanced stage of deterioration (at least next to the surface) and that pulverization was caused by the stripping of the outer thin crust.

Change in Specific Gravity of the Material During the Construction Period.—Table 3 suggests that, in the case of the Conn Valley Dam, in Napa, Calif., in the three borrow pit areas, the material became finer after compaction and its specific gravity increased. The decrease in the coarseness of the material that undergoes compaction is easily understood, especially if the material contains breakable rock fragments.

The fact that the specific gravity of an earth material may change as a result of hydration or dehydration is clear to anyone who remembers how, from two metals of different density, an alloy of intermediate density may be obtained.

In the case of hydrated clay and similar materials, water broken into hydroxyl and hydrogen ions joins the atoms of the clay minerals located at the

[12] "Etude des détériorations des pierres des monuments historiques," *Annales*, Institut Technique du Bâtiment et des Travaux Publics, Paris, December, 1949.

crystal lattices and "dilutes" their solid substance. The latter, however, still remains solid after hydration. The specific gravity of the hydrated product in many cases may be simply computed in the same way as the specific gravity of an alloy is computed from that of the two original metals. The tamping effect perhaps produces dehydration by throwing the components of constitutional water off the lattices, especially if that water is loosely accommodated at the lattices. It remains to be determined, more precisely, under what circumstances dehydration may take place during compaction.

Again, is it possible that compaction may produce the base exchange and thus replace lighter atoms by the heavier ones, or vice versa? These and similar questions should be clearly answered for the benefit of engineers who specialize in compaction problems; and, to obtain such answers, careful additional field investigations, and possibly extensive laboratory research, are needed. Mr. Forbes' paper is a valuable beginning of the scientific study of a complex array of interesting and important geotechnical problems, compaction being only one of them; and the author is commended for having brought these problems to the attention of engineers.

S. S. GORMAN,[13] M. ASCE.—The subject of geochemistry applied to soils as foundations and in earthwork is not new to the Foundations and Soil Mechanics Committee of the San Francisco (Calif.) Section of the Society or to the San Francisco Section as a whole. The author (whose membership in the Foundation Committee dates from April, 1929) has frequently discussed the subject, and at the regular meeting of the section, April 21, 1931, presented an abstract in his section of the report of the committee on the question of subsidence and the foundation problem in San Francisco. This report was published by the section in September, 1932.

The writer has worked with the committee since 1939 in the study of related problems. The work of the committee was again presented at the regular meeting of the section on October 18, 1938. The author's paper was entitled "Geological Background of Soil Behavior" and was made available only to section members in the *Proceedings* of the section. In that paper, it was emphasized that soil is not a static thing but, when accumulated in its various land forms, changes of a physical and chemical character continue until all rock fragments are completely broken down to clay and grit.

Rock originated in the molten state, crystallizing out in the form of complex silicates. Soil in addition contains oxides, carbonates, sulfates, and chlorides derived through rock weathering and geologic processes. The mineral constituents of the soil are continually being attacked by chemical reagents. Oxidation and carbonization take place, forming new oxides and soluble carbonates. Hydrolysis of the oxides silica, alumina, and ferrous oxide, as well as of the sulfates and chlorides of the bases continues, reducing the soil particles to colloids.

Furthermore, rock is not always stable but, due to the forces of nature, breaks down under general geologic processes. The processes involve both mechanical disintegration and chemical decomposition which are frequently the cause of landslides and rockfalls in cuts. It has been found that instability

[13] Asst. Chf. Engr., Board of State Harbor Commrs., San Francisco, Calif.

results because of profound geochemical changes occurring in rock which are not attributable to surface weathering.

As regards the determination of the effect of such geochemical change, a practical application was made by the author in his investigation of and recommendation for the correction of an area of unstable hill in the San Francisco Naval Shipyard in 1947 as a basis for work contracted for by the writer's department. It was found that the original peridotite underwent serpentinization (a process of hydration) which caused a pronounced internal shearing movement resulting in a thoroughly slickensided mass of cohesionless, dark colored to black serpentine rock particles, in which sheared diabase sills occurred and over which a massive sandstone and chert formation had been completely shattered and crushed through the displacement caused by the swell in serpentinization.

These conditions were not revealed until partial excavation was undertaken, slides were developed, and test borings were made. Correction consisted in resloping the hill area to meet the rock conditions involving the removal of many thousands of yards of material.

CHARLES H. LEE,[14] M. ASCE.—A most intriguing field for research and one which may have great potentiality for the engineer interested in earthwork has been touched upon by Mr. Forbes. Through this field an engineer may ultimately attain a technical command of earth material which in some instances may approach that of the metallurgist in the field of alloys, or of the chemist in the production of synthetic materials. The scope of scientific knowledge on which such command will be based, however, is far broader than geochemistry. It includes geochemistry and mineralogy as well as a specific knowledge of all phases of the clay minerals and of the mixtures of clay and nonclay minerals. It involves the physical chemistry of colloids, the flocculation and dispersion in clay suspensions (when ions are present), and the chemistry of adsorption in pasty masses where the ratio of solids to liquids is relatively high. A knowledge of the structure and behavior of soil crumbs or flocs built up by the attachment of ions adsorbed out of solution onto a nucleus of inert particles is also involved. As stated by the author, it also requires a knowledge of the various chemical processes met with in geochemistry, such as hydration and dehydration, base exchange, oxidation and reduction, and loss or addition of gaseous components. In short, it includes not only geochemistry but also the fields of soil physics, soil chemistry, ceramics, the physical chemistry of natural cements, and many other fields of scientific knowledge.

To be of value, the results of research in any new field of human endeavor should be supported by evidence of a convincing character and must also be related to the systematized knowledge of those branches of science to which it pertains. The results of research must also be expressed in generalized form and must be provided with technical procedure such that practical workers can take it and apply it to the varied problems that confront them. This is particularly true in a new field of activity, such as the application of chemistry to earthwork, where the entire subject is still in an immature state. The paper illustrates the

[14] Cons. Engr., San Francisco, Calif.

current awakening to a new phase in the handling of earth in engineering construction.

Essential to any engineering study of clays or of altered rocks is identification. Often it is necessary to identify the mineral constituency of the rock both in its original condition and as modified by weathering or hydrothermal processes. Such identification should extend to internal texture, structure, and mineral composition. If the slow chemical changes that take place in nature can duplicate, continue, or reverse themselves with rapidity in manipulated earth (as suggested by the author), then identification of the beginning and end products should furnish conclusive proof. Modern petrographic methods as applied to engineering problems provide a valuable tool for this purpose. Petrography as now practiced includes, in addition to petrographic analysis, microscopical examination, microchemical analysis, X-ray diffraction analysis, differential thermal analysis, and various physical tests. Undoubtedly the paper could be strengthened by submission of petrographic or other proof that the "geochemical processes of nature * * * are duplicated or continued by the methods of engineering construction" (see under the heading, "Geochemical Change Accompanying the Handling of Earth").

Considering the paper more in detail, the author points out that earth is a mixture of mineral and organic solids with water and gases. He indicates the various changes which he believes take place in these components during the handling and compacting of earth in construction operations. These changes can be classified as follows: (1) Reduction in particle size; (2) alteration of the chemical constituency of the solid particles, and hence of their specific gravity; (3) effect of the chemical elements dissolved in the soil water; and (4) cementation through chemical action produced by compaction.

The author attempts to identify these changes with the more or less well-recognized changes that occur in rock materials during long periods of geological time, as the result of weathering and hydrothermal activity. He intimates that in manipulated earth these changes take place in a matter of hours, days, or years, instead of millenniums or eons.

With regard to the reduction in particle size, in the examples presented by Mr. Forbes, it is to be noted that the mechanical analyses to determine percentages of various particle sizes were made by sieving. The only pretreatment mentioned is that of washing out the fines, drying them in an electric oven, and breaking them up with a wooden roller, or breaking the soil by hand on the screens in an air-dried condition. Apparently no attempt was made to break up the soil particle aggregates by chemical pretreatment and vigorous stirring or long, continual shaking of the test sample in suspension. In making mechanical analyses of material similar to those described by the author the writer has found that, without such pretreatment, appreciable percentages of the particles held on the finest mesh are composed of soil particles aggregated into crumbs (flocculated) which, if subjected to the standard treatment followed in hydrometer analysis, would separate into their pre-existing smallest particle sizes (deflocculate). It is believed that the reduction in particle size indicated in Tables 1, 2, and 3 would not have appeared if the mechanical analyses had been performed by present-day methods as standardized by the American Society for Testing Materials (ASTM) and other agencies. Excavating from

borrow pits, air drying in stock piles, and mechanical handling accomplished a measurable degree of breakdown which sieving alone failed to accomplish.

Change in the structure of a soil particle through chemical reaction, with the removal or addition of an element or radical comprising an integral part of the structure, constitutes alteration of the chemical constituency of the solid. Such change does not include a change in the adsorbed film of water around or within the cellular structure of soil particles, or a change in the ions or radical in solution in such water. Change in the chemical constituency of solid particles of rock or soil may take place through various processes, such as the addition or removal of constitutional water (including water of crystallization), oxidation or reduction, chemical breakdown of complex unstable compounds, solution, or the action of organic acids or strong alkalies. Most of these reactions proceed very slowly and for their occurrence require conditions which are not present in earth construction. Most important of these conditions is free circulation of soil water through the voids between solid particles which is necessary for solution, oxidation, and reduction, and the continued action of weak acids or alkalies. Circulation is required to maintain the reaction and to carry away its products. Long continued circulation of water through the soil, or through the joints and cracks of the rock, is an essential accompaniment of weathering, hydrothermal activity, the formation of caliche or hardpan, and other geochemical processes. Circulation of water does not take place in clayey materials compacted to the degree of impermeability required for storage dams of earth. In fact, one purpose of compaction is to prevent such circulation.

Change in specific gravity accompanying alteration in chemical constituency is probably infrequent in earth construction and is attested by the fact that standard ASTM and other procedures for making soil compaction tests do not provide for such a contingency in establishing the zero voids curve. The necessity for such provision is apparent, if changes of from 4% to 6% in specific gravity can take place in handling and compaction, as is indicated in Tables 3 and 7. Even greater percentage increases in specific gravity are represented by changes of from 2.3 or 2.5 to 2.6 or 2.9 stated by the author to accompany dehydration. Moisture differences between the actual and zero voids moisture curves vary greatly—from 2% to 5%. Discrepancies of from 4% to 6% or more in specific gravity, if of frequent occurrence, would have given trouble in analyzing the test results of compaction and would have become generally recognized by soil technicians. This has not been the case. The author states that all materials compared in Table 3 are valley fill and alluvium from the vicinity of the dam site. It has been the writer's experience that such materials from a limited area do not vary in specific gravity to the extent indicated for the borrow-pit samples—namely, 2.574, 2.462, 2.446, and 2.707. Light might be thrown on the matter if the author's method of determining specific gravity was detailed, and if information was furnished regarding the predominant chemical constituency of the various samples.

The author presents various examples of the effect of the chemical elements dissolved in the soil water. Experience with sea water in compaction at Swanzy Dam (Vallejo, Calif.) recalls the writer's use of sea water in sealing the pervious clay lining of the Exposition Lagoon at Treasure Island (San Francisco, Calif). Base exchange of sodium and calcium ions existing as electrolytes in

the soil water was involved in both instances. The author states (under the heading, "Water: Effect of Water in Earth Fill Construction, Swanzy Dam"): "The compacted material proved to lack cohesion and when air dried, it was loose and crumbly." This flocculated condition was overcome by the writer by leaching with fresh water. As stated elsewhere,[15]

> "After leaching with fresh water to remove excess sodium ions from the soil-water solution, the colloidal aggregates disperse, changing the physical properties of the soil and filling the voids with a sticky colloidal gel which is impervious to water."

An essential feature of the employment of base exchange to alter the physical properties of a soil is the removal of excess electrolytes. This was discovered before 1915 by soil physicists in experimenting with alkali soils in California.

The author believes that cementation through chemical action takes place in the process of compaction and he cites, as comparable examples, the formation of hardpan and caliche in alluvial deposits of the West. This explanation of the cause of the stiffening and hardening that occurs in clayey materials during the compacting process is quite at variance with the current concept—namely, that it is the result of closer contact and interlocking of soil particles, bringing a greater proportion within the range of molecular attraction as well as increasing the viscosity of the colloidal gel surrounding soil particles by attachment to them of increasing numbers of free ions from the soil water. The paper needs to be strengthened by submission of petrographic or other specific proof in support of this novel thesis.

GEORGE S. HARMAN,[16] ASSOC. M. ASCE.—The attention of the writer was first called to geochemical change taking place in rock in 1935, in connection with the stabilization of the slope in the James D. Phelan State Park Beach in San Francisco, Calif. The serpentine rock extended up the slope beneath dune sand, above the high-tide line. Surface water draining through the dune sand to serpentine rock caused the rock to hydrate rapidly. In so doing, it swelled and absorbed more water until what had been rock a short time before flowed over the beach sand as a green slime. At that time, intercepting drains were installed over the most unstable part of this area to keep surface water from accumulating above the rock. Continued observation since that time indicates that the slope has been stabilized in the area drained. However, another part of the site which seemed to be stabilized in a natural way (there being a free flowing spring) became unstabilized and started to slide. It became apparent that the entire area should be thoroughly investigated, and an extensive drainage system, both surface and subsurface, has been designed by the Department of Works, Bureau of Engineering, at the request of the Recreation and Park Commission of the City and County of San Francisco.

The author mentions briefly the effects of the geochemical change accompanied by the surface settlement of the rock fill placed from 1930 to 1933 to provide level surfaces at St. Mary's Playground in San Francisco.[4] Although

[15] "Sealing the Lagoon Lining at Treasure Island with Salt," by Charles H. Lee, *Transactions*, ASCE, Vol. 106, 1941, p. 579.

[16] Supervising Engr., Recreation and Park Dept., San Francisco, Calif.

[4] *Transactions*, ASCE, Vol. 112, 1947, p. 399.

accurate, precise level records were not kept to measure the settlements in this fill, the magnitude and rate at which it settled was far more than originally expected, disrupting walls and rock gutter drains. The original fill was made of sandstone fragments varying in size to blocks of approximately 12 in. in diameter. The sandstone, characteristic of a considerable area in San Francisco, contained calcium carbonate as veinlets and as filling in the pores, binding the grains together. There was a large percentage of voids in the fill, as placed; 36-in. holes were readily bored through the fill in 1941–1942 and they did not have to be cased. The walls of the boreholes soon became covered with a white efflorescence, explained by the author to be lime (CaO) left by the breakdown of the calcium carbonate of the rock, releasing carbon dioxide. The carbon dioxide was absorbed by the circulating water to form carbonic acid, which further attacked the minerals making up the rock, achieving in time the present compact sandy clay.

In San Francisco, bedrock slopes are steep. The overlying material consists, usually, of interlayered clay and sand due to intermittent accumulations of wind-blown or dune sand over weathered soil surfaces; and ground-water conditions are an important factor in strength and stability. The level areas are principally made by cutting and placing fill. Much of the fill consists of sand derived from leveling the dunes, but the upper thicknesses in many filled-in locations are the rubble left by the 1906 fire, and a miscellany of material. Most of the level areas of the city playground sites involve both cut and fill.

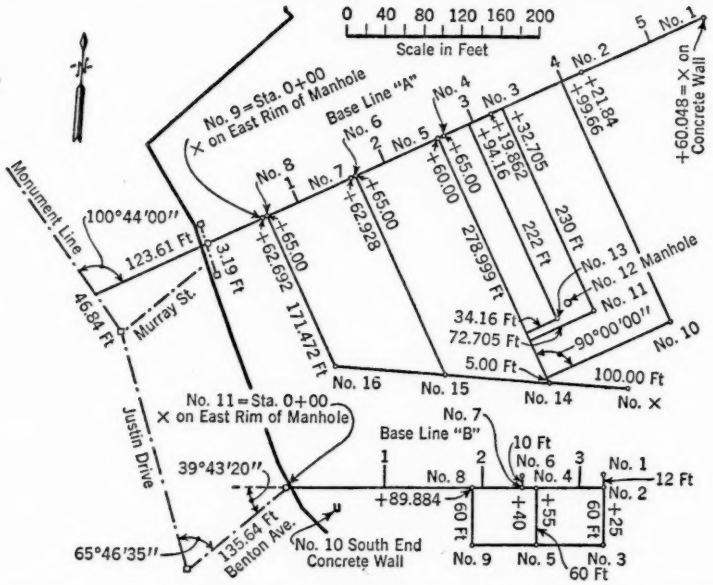
A bond issue of $12,000,000 was voted in November, 1947, to cover improvements on fifty-three separate recreational areas, involving concrete structures on some of these sites costing up to $350,000. On eighteen sites—because of either the proposed structure or the geological and ground conditions—it was decided that a consultant should be employed to investigate and advise the writer and the architect for the commission as to the allowable bearing capacity of the sites.

The St. Mary's site was one of the first investigated, and it was found that compactive settlement, and the change in the fill, had practically ceased (see Table 9). The material had achieved an average density of 108 lb per cu ft, dry, and developed enough shearing strength to support the structures planned. It was apparent therefrom that geochemical change occurring in fills is an important factor in their supporting value as well as in their stability.

The Potrero Hill building site, also in San Francisco, consisted, in part, of a rock fill blasted from the remainder of the site to provide a level area; this was done in 1931. The measured settlement has been slight. Test-pit excavation revealed the fill to be composed of highly siliceous rock of igneous origin, which suffered little, if any, decomposition but some crushing. The voids between the component rocks were still large, and the safe bearing capacity was judged to be 1,750 lb per sq ft, which required the spreading of column footings to cover 21 sq ft of bearing area.

The effects of age, character of material, penetration, and occurrence of water therein were investigated at the remaining sixteen sites. A number of the sites consisted of fills comprised largely of dune sand. Where the fills had been surfaced by impervious materials for tennis and basketball courts, the

TABLE 9.—Subsidence Record, St. Mary's Playground, San Francisco, Calif.



Point No.	Elevations, in Feet, Observed on:							Movement	
	Aug. 31, 1944	Nov. 21, 1944	Feb. 7, 1945	April 9, 1945	May 15, 1945	June 13, 1945	July 27, 1945	Feet	Direction
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
					(a) Base Line A				
1	151.644	151.636	151.642	151.648	151.649	151.644	151.645	0	....
2	150.274	150.293	150.294	150.300	150.300	150.295	150.296	0	....
3	150.538	150.551	150.558	150.558	Stake lost	....	....	....	....
4	150.370	150.377	150.379	150.382	150.384	150.375	150.375	0	....
5	150.230	150.233	150.236	150.244	150.248	150.238	150.235	0.010	North
6	150.554	150.566	150.568	150.571	150.573	150.559	150.555	0	....
7	150.594	150.619	150.622	150.623	150.621	150.605	150.604	0	....
8	150.297	150.302	150.300	150.303	150.307	140.300	150.301	0.005	East
9	154.931	154.931	154.934	154.933	154.933	154.931	154.931	0	....
10	144.866	144.856	144.891	144.902	144.895	144.880	144.872	0.03	South
11	145.479	145.466	145.461	145.470	145.460	145.446	145.441	0.02	South
12	146.344	146.341	146.339	146.347	146.345	146.342	146.342	0	....
13	146.166	146.166	146.160	146.172	146.168	146.162	146.158	0.02 0.01	South East
14	145.229	145.228	145.240	145.248	145.247	145.238	145.227	0.006	South
15	146.189	146.180	146.192	146.199	146.195	146.187	146.181	0.02	South
16	147.430	147.430	147.433	147.439	147.437	147.422	147.419	0.05	South
X	115.958	115.937	115.956	115.962	115.949	115.948	115.936	0.02	South
					(b) Base Line B				
1	118.608	118.617	118.609	118.607	118.594	118.587	118.585	0	....
2	118.740	118.752	118.748	118.752	118.737	118.729	118.724	0	....
3	117.824	117.817	117.836	117.837	117.827	117.815	117.797	0.04	South
4	120.817	120.824	120.823	120.821	120.812	120.809	120.798	0	....
5	119.508	119.497	119.503	119.504	119.499	119.491	119.472	0.01	South
6	120.744	120.814	120.824	120.819	120.818	120.743	120.728	0	....
7	121.164	121.179	129.177	121.175	121.166	121.163	121.152	0	....
8	120.936	120.946	120.946	120.948	120.940	120.936	120.928	0	....
9	119.848	119.841	119.879	119.881	119.871	119.855	119.829	0.02	South
10	123.330	123.328	123.324	123.322	123.323	123.328	123.330	0	....
11	128.913	128.917	128.917	128.918	128.918	128.915	128.912	0	....

underlying sand was found to be unchanged and to have characteristics similar to those described by the author (under the heading, "Water: Fort Ord Reservoir in California, Proposed As Balanced Cut and Fill"). The latest sand fill, in point of age, consisted of fresh dune sand whose dry density ranged well under 100 lb per cu ft. Cohesion was slight, the maximum cohesion of the core samples tested being 175 lb per sq ft, and the low value obtained for shearing strength under the existing surcharge and other considerations limited the bearing value to 1,500 lb per sq ft.

Hamilton Playground, however, occupies a sand fill since the sand dunes were leveled and the depressions were filled along Geary Street in this part of San Francisco before the turn of the century. It has long been landscaped and subject to rainfall penetration. The sand is classed as cohesionless, the average value for the core samples tested being 240 lb per sq ft. Streaks of sand in the mass were red and yellow-brown in color, because of the production of minerals through the oxidation and hydration of the original iron minerals of the dune sand, in association with water through rainfall penetration. These minerals produced some cementation, but it did not provide the sand the tenacity of "soft sand rock," described by the author in connection with the Sutro Forest Reservoir. That iron was carried in solution through the sand was shown by the fact that, from 10 ft to 11 ft below the surface of the fill, a piece of coal was brought up in the core sample which had been entirely coated with crystals of iron carbonate—the result of chemical reaction by water-carried minerals in solution with the carbon of the coal. The resulting change in the mineralogical character of the sand was reflected in the bearing capacity of this fill which, based on laboratory tests, was judged at 4,000 lb per sq ft.

HYDE FORBES,[17] M. ASCE.—A broad subject is involved in the consideration of geochemical changes taking place in natural material, with soil development, and during the working and placing of that material. The writer, constrained to brevity, realizes that he has barely "scratched the surface"; he generalized on the basis of his experience and hoped that discussion would add breadth to the present consideration. However, it was not contemplated that the broad fields noted by Mr. Lee, at the close of his opening paragraph, be considered. The writer has relied on his basic knowledge of geology, mineralogy, and chemistry in interpreting the geologic origin and the geochemical development of natural materials, and has used simple, well-known tests as a measure or "yardstick" in applying that interpretation.

In his discussion, Mr. Smith, a geologist, suggests that civil engineers should have more geology in their curriculum. It is also suggested that: "It is not enough to hire a geologist and leave the problem entirely to him"—inferring that the geologist lacks sufficient knowledge to apply geology to engineering problems. In a letter once received from William P. Creager, Hon. M. ASCE, it was stated: "Too many engineers know too little about geology and too many geologists know too little about engineering." That is true, and the field of specialization in engineering geology requires that a student major in civil engineering long enough to obtain a working knowledge of the fundamentals,

[17] Cons. Engr. and Geologist, Palo Alto, Calif.

then he can study geology objectively, not only as a pure science. The writer has previously submitted his proposed curriculum.[18]

Mr. Harman's discussion "points up" the importance of understanding equilibrium relationships in soil technology in interpreting the results of core sampling and the tests made on such samples in foundation investigations. The effect of water penetration, forming solutions, through material placed in fills or natural soils, is to provide an opportunity for the exchange of mineral ions at the suface of each soil particle and ions held in solution by water. This fact is illustrated by Mr. Harman in the reaction between water and coal in a fill. Such exchange leads to a change in the geochemical character and the physical behavior of the material. The soil particles tend to reach chemical equilibrium with the water so that an equilibrium distribution of the ions between the soil and the solution is approached. Secondary concretionary minerals, hydrous hematite and limonite streaking the Hamilton Playground sand mentioned by Mr. Harman, for example, are dehydrated; carbonates of the alkalies are formed, binding the particles of well-drained or dried soil together, thus increasing its resistance to shear, and increasing its supporting value.

Under the heading, "Field Decomposition of Calcium Carbonate," Mr. Krynine presents interesting examples of geochemical change involving calcium compounds. The foundation rock beneath the sand and gravel of the stream bed at the Gibraltar Dam was fresh as a result of scour. It is quite possible that it could have been affected by leaching below an apparently solid crust. However, the wire brushing and the immediate placement of concrete over the bedrock were successful in producing a watertight bond that proved satisfactory for thirty-five years. Both Messrs. Krynine and Lee discuss the changes in specific gravity of particles with working. Soil contains a large number of minerals among other matter so that an exact analysis and computation of specific gravity mathematically would appear impossible. The concept of the writer is a combination of those presented by Mr. Krynine—namely, dehydration of some minerals and base exchange effected through kneading action in the presence of water during the working of the soil. Mr. Lee asks that the method of determining the specific gravity be stated. The fine granular soil particles are made up of many crystalloid minerals; mineral and organic matter, either amorphous or colloidal; and gravel or rock fragments of larger size which are usually combinations of several minerals. Therefore, the average-particle, specific gravity of a soil is all that can be determined. This is most readily done in a specific gravity flask. The Le Chatelier apparatus, used by the writer in his tests, is available on most jobs where concrete batching or testing is being done.

The soils over a large area in Oregon are derived from volcanic sources and it would have added to current knowledge of their behavior had Mr. Smith presented the data obtained as the result of his investigations, which were presumably of a "katamorphic" nature according to his description. Since the preparation of the paper, the writer has had opportunity to investigate kaolinitic, ferruginous, and bentonitic clays derived from volcanic material, as well

[18] Discussion by Hyde Forbes of "Geology in Highway Engineering," by Marshall T. Hunting, *Transactions*, ASCE, Vol. 110, 1943, p. 337.

as pumice, in Oregon. With proper selectivity and treatment, the origin and development of those clays proved to be subject to a development classed as "anamorphic," in Mr. Smith's description. The origin and development may be of interest and the tests thereon answer questions raised by Mr. Lee's discussion. The "borrow" for the impervious clay core of the Toketee Diversion Dam of the California Oregon Power Company, on the North Umpqua River, consisted of a meadow in an oxbow of the river upstream from the site, and subject to overflow. The original overflow deposits consisted of pumice and andesitic sand, silt, and rock flour, with some basaltic sands and boulders. The humic and carbonic acid, picked up by waters passing through the vegetation and top soil, effected carbonization of the alkaline aluminum silicates, thus producing a kaolinitic clay (hydrous aluminum silicate), and released the alkaline minerals, which now occur as carbonates. The moisture content of the clay ranged from 50% to 80% of its dry weight; and it had to be processed through plowing and disk harrowing to dry it out for optimum compaction. When first stripped and plowed, the clay appeared as black clods which, when broken up and dried by the harrows, turned white in color (oxides of the alkalies) and broke into dust-size particles even with a moisture content of 25% by weight. When the material was compacted in field tests, and when it was compacted into the dam, the color changed to a dark gray, the carbonates reforming.

Mr. Lee found that variation of specific gravity within the same borrow area does not reach the extent cited for the Conn Valley Dam. The writer has found that such determinations vary widely from borrow area to borrow area and between test boreholes within the same borrow area as well as between samples from the same test boring; 54 test borings were made at 100-ft centers over the Toketee clay borrow area, and as many as 4 samples from each hole were selected for test. The content of unchanged pumice was relatively high in most holes and the variation in the specific gravity ranged from 2.169 to 2.45 in all samples. In a single hole, the specific gravity of the samples varied from 2.245 to 2.45. The average specific gravity of the borrow-pit samples was 2.37. The samples cut from the dam varied in specific gravity from 2.30 to 2.70, the average being 2.49. In the field compaction tests, and with rolling into the dam, the carbonates were regenerated and had the effect of cementing and hardening the clay. Tested at 20% moisture content, the compacted dry weight was 95 lb per cu ft. Cohesion was found to be 2,750 lb per sq ft, and the shearing strength under a surcharge of 5,000 lb per sq ft was 8,000 lb per sq ft. Practical considerations in working made it impossible to achieve optimum density which occurred when tested at 105 lb per cu ft (dry weight) compacted with 16% moisture content. The gray clay was found to be impervious and able to stand in a vertical face when the clay core was cut through to its foundation for installation of permanent closure.

The bright red clay at the site of Fish Creek Diversion Dam and Forebay (on a tributary of the North Umpqua River) consisted principally of hydrous hematite derived from the decomposition of basalt. The hematite blankets the basalt to depths of as much as 35 ft and in turn is blanketed by pumice ash. Similar variation in specific gravity determinations between borrow-area samples

was found here, averaging about 2.46. The determinations made on samples cut after rolling showed an increase varying from 2.50 to 2.85 in specific gravity. Both the kaolinitic and ferruginous clays made excellent bonds with concrete and abutment rock. The Willow Creek Dam of the City of Medford, Ore., lies within a volcanic watershed and the reservoir site is the borrow area. The dam is to be built in 1951 but the preliminary tests on the available construction material show results consistent with the previous experience of the writer—namely, that there is an increase in specific gravity, with working, as minerals of higher atomic weight are formed under treatment and under a construction control designed to meet the mineralogical character of the material used.

Mr. Lee suggests more refinement in the determination of grain distribution than the sieve sizing used by the writer. The acid and other treatment suggested by Mr. Lee seems to defeat the purpose because it gives ample opportunity for the breakdown of individual grains and fragments. The writer has learned to keep test procedure as simple as possible, but always to conduct the tests in the same manner so that the results will be comparable. The material in question (natural material including soil) is extremely variable, and there is a large human equation for all test procedure devised in soil mechanics. Therefore, absolute determinations are not warranted and comparative results will prove to be ample. In the matter of compaction all test results are comparative. The maximum dry density which it is possible to achieve under optimum moisture varies greatly. The writer terms the absolute density as the percentage of the weight of materials in solid dry mass. That definition necessitates the determination of the specific gravity of the particles making up the mass and gives the percentage voids by volume. For example, the compacted dry density of some samples obtained at Toketee Dam was as low as 61% of absolute, which gives 39% voids. Such a voids content in granular material of larger size would mean permeability, but the grain-size distribution curves of the dam samples showed an average of more than 50% smaller than 1.0 mm and a clay content determined by elutriation of more than 30%. These tests are made quickly and at little cost; they are most informative during, as well as before, the construction period. The writer had adapted the same type of simple tests to foundation and stability investigations, not as a substitute for an understanding of the mineralogical and geological nature of the material and the processes through which it has emerged, but as an added tool in exercising geological judgment.

The profound geochemical change in the rock mass making up the hill area at the San Francisco Naval Shipyard, described by Mr. Gorman, not only had a considerable economic effect on the works constructed at that location, but has added greatly to the costs of other public works in San Francisco. The peridotite intruded originally into massive sandstone and chert beds, to be uncovered through erosion from Hunter's Point northerly across the city to Fort Point, the south end of the Golden Gate Bridge. The swell of the peridotite in serpentinization exerted enormous pressures so that the sandstone and chert bordering the mass are found completely crushed, with fracturing extending outward from that area. Such crushed zones become clay with the penetration of water, and are unstable, subject to slide, when disturbed through excavation (as at the

Parker Avenue Landslide at Lone Mountain).[19] In addition, the overlying sandstone formation has been deformed and subjected to overthrust. The overthrust extends many miles in a north-south direction through the built-up area of the city. The entire mass involved in the overthrust is cylindrical in section, one border making up the top and east face of Telegraph Hill and the other border making up the top and west slope of Russian and Nob Hills. Examples of the horizontal shear planes along which movement occurred at many levels in the mass can be seen near the top of the massive sandstone making up the east face of Telegraph Hill. Those having an opposite dip can be seen in cuts on the ridge of Russian and Nob hills. The excavation for the North Point Sewage Treatment Plant at the toe of the north slope of Telegraph Hill resulted in moving ground as the sheared, thoroughly slickensided rock of the zones of shearing raveled out and the horizontal sandstone masses were not able to cantilever over, unsupported. The results of the diamond drilling along Broadway indicate that the vehicle tunnel under that street will encounter horizontal shear zones of the westerly limit of the overthrust.

[19] "Landslide Investigation and Correction," by Hyde Forbes, *Transactions*, ASCE, Vol. 112, 1947, p. 381.

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